# Ultrasound Visualization Using Polymer Dispersed Liquid Crystal Sensors

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**Abstract.** The acousto-optic effect in liquid crystals (LCs) has previously been exploited to build large area acoustic sensors for visualising ultrasound fields, opening up the field of acoustography. There is an opportunity to simplify this technique and open new application areas by employing polymer dispersed LC (PDLC) thin films instead of aligned LC layers. In PDLCs, the normally opaque film becomes transparent under the influence of an acoustic field (e.g. when surface acoustic waves are propagating in the material under the film). This is called acoustic clearing and is visible by eye. There is potential for producing ultrasonic sensors which can be 'painted on' to a component, giving direct visualisation of the ultrasonic field without requiring scanning. We demonstrate the effect by using PDLC films to characterise a resonant mode of a flexural air-coupled transducer. Visualisation was quick, with a switching time of a few seconds. The effect shows promise for ultrasound sensing applications for transducer characterisation and NDE.

## INTRODUCTION

Liquid crystals (LCs) are becoming a part of everyday life, with the most obvious applications being their use in displays. A LC is a material which has some order, with the level of ordering sitting somewhere between a highly ordered crystal (order parameter of 1) and a liquid (order parameter of zero). An LC may have some orientational order but no positional order, with an order parameter of between 0.3 and 0.9 [1]. LC displays contain a thin layer of LC which has been aligned, and is held between two plates. When a field is applied, for example an electric field generated by nearby electrodes, part of the layer will re-align. LCs are optically birefringent, and hence the optical properties in the realigned region are different to those in the main layer; by using polarisers an image can be displayed [1].

A similar effect occurs when an ultrasound sound field is applied to an aligned LC layer; this effect is known as the acousto-optic effect [2-4]. In this, a sound field which is incident on the LC layer causes local reorientation. The acousto-optic effect has been used to produce an ultrasound sensor for use in NDE [5,6]. The acoustography system uses a thick (around 200 μm) layer of aligned LC held between two glass windows. These are sat in a water bath, along with a sound source and the sample under investigation. As the sound wave is incident on the sample, it will be transmitted through regions where the sample is whole, and reflected away from the LC sensor if the sample contains defects such as cracking or voids. The transmitted wave field, once incident on the LC sensor, will cause realignment in certain regions. By use of polarisers, areas in which the sound wave has been blocked are shown as dark areas, whereas areas where the ultrasound reaches the sensor lead to a change in alignment and give a bright area. Operation is typically at a frequency of 3.3 MHz [5,6].

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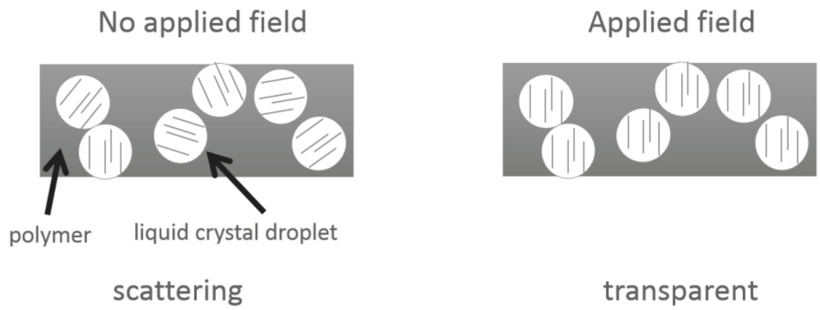


**FIGURE 1.** A representation of the acousto-optic effect in a PDLC layer, showing the progression from scattering to transparent on application of an external field, for example ultrasound waves.

## Polymer Dispersed Liquid Crystals

Recently, a similar effect has been shown when using polymer dispersed liquid crystals (PDLCs) [7,8]. Surface acoustic waves were propagated along a sample, and were shown to produce acoustic clearing in a PDLC layer. A PDLC consists of droplets of LC held in a polymer layer, with a schematic shown in figure 1. The layer is typically thin, around 20 μm. With no external field applied the orientation varies randomly from droplet to droplet [9,10]. An applied field will align the liquid crystal droplets within the polymer matrix, leading to a change in properties. Using PDLC in place of LC can lead to significant simplification in the experimental procedure, and could potentially give the required step change in NDE, enabling inspection of a system by using a 'smart paint' [11].

The LC has refractive indices of $n_o$ when aligned in one direction, and $n_e$ when aligned perpendicular to this. The refractive index of the polymer is chosen carefully to match that of one chosen alignment, $n_o$. In the un-aligned state, the effective refractive index of each droplet varies randomly from $n_o$ to $n_e$ due to the random orientations, producing very strong scattering of light. This gives a material with a milky, opaque appearance. When the LC droplets are aligned due to the application of an external field the composite material stops being scattering, and instead becomes optically homogenous, at which point light can pass through and it appears clear [7]. This enables direct visual observation of any alignment, without requiring polarisers or the material to be pre-aligned, giving potentially a much simpler implementation of acoustography. In addition, the PDLC can be directly applied to the sample; it will produce a flexible, adaptable sensor. No liquid couplant is required [11].

## EXPERIMENTAL DETAILS

In the experiments described here PDLC layers were produced on top of several transducers to demonstrate the acousto-optic effect for transducer characterization. A thin paint layer can be added to provide optical contrast but is not required for operation. A thin cover slide, such as a glass microscope slide, is added to constrain the PDLC layer and to improve coupling of the ultrasound into the film. A schematic of the set-up is shown in figure 2, with the acousto-optic effects visible by eye.

The PDLC layers were produced using carefully chosen materials; the type of LC chosen was E7, and a NOA74 Norland adhesive was chosen as this has good mixing with E7 and a suitable refractive index. The layers contained 76% LC. Droplets were around 3 μm in diameter and the layer had a thickness of 100 μm. Layers were produced on several different ultrasonic transducers to demonstrate different effects. Initial measurements used longitudinal wave transducers with an operating frequency of 2 MHz. Later experiments used flexural transducers [12] which are composed of 25 mm diameter aluminium caps and a piezoelectric transducer. These caps can resonate in different modes, with the mode presented here the (0,11) axisymmetric mode at a frequency of 730 kHz. The application of a contrast paint layer led to a small variation in the resonant frequency, but within acceptable parameters. Continuous sine-wave signals were generated using a function generator and an amplifier. Prior to application of the contrast paint and the PDLC layer the flexural transducers were imaged using a Polytec vibrometer with a bandwidth of 2 MHz. Measurements took around 8 hours to produce a wavefield image of a single resonant mode [11].

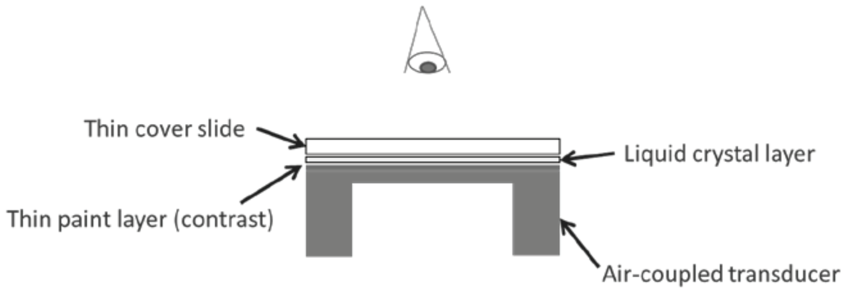


**FIGURE 2.** Experimental set-up showing transducer, PDLC layer, and visualization by eye.

## RESULTS

Initial measurements used a PDLC layer produced on a 2 MHz longitudinal wave transducer. A pattern was drawn underneath the PDLC layer to improve contrast and demonstrate the acoustic clearing effect. Results are shown in figure 3, with the milky appearance of the PDLC layer clearing on application of the ultrasound field, leading to a clearer pattern observable underneath the layer. Images were produced at the same time to ensure the focusing of the camera was consistent between images. However, it is well known that generation of ultrasound will have some heating effects, which can also clear PDLC layers, and further tests were required.

To demonstrate that acoustic clearing is possible using PDLCs, another PDLC layer was produced on a flexural transducer [11]. These are produced for air-coupled ultrasound experiments, and it is important to understand the resonant mode patterns produced in order to understand the wavefield which will be generated at the sample [21]. Imaging typically uses techniques such as laser vibrometry to measure surface displacements or velocities, but these require point-by-point scanning and can take several hours to produce a full image.

Figure 4 shows two images produced using different techniques. On the left is a photograph of the clearing produced in a PDLC film on top of the flexural transducer, with the transducer operating in the (0,11) axisymmetric mode. This shows a series of cleared and opaque rings, corresponding to regions of high and low amplitude vibrations. Clearing took around 30 s to start due to a requirement for some pre-heating of the PDLC layer, but once it was warmed up the clearing and relaxation back to opaque took around 1-2 s. On the right is the wavefield as imaged by the Polytec vibrometer. This again shows a series of rings of high and low amplitude vibration.

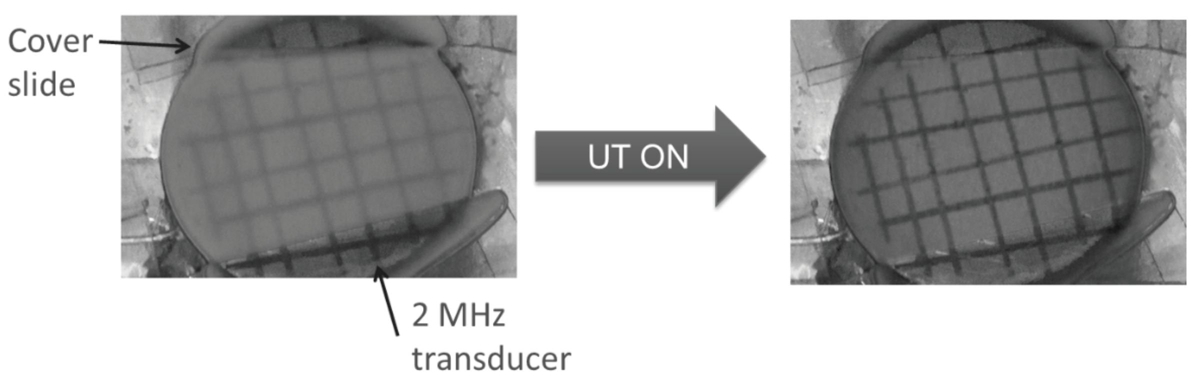


**FIGURE 3.** Clearing demonstrated on a 2 MHz ultrasound transducer. In the left image the transducer is switched off and the PDLC layer has a milky appearance. In the right image the transducer is switched on and clearing is observed.

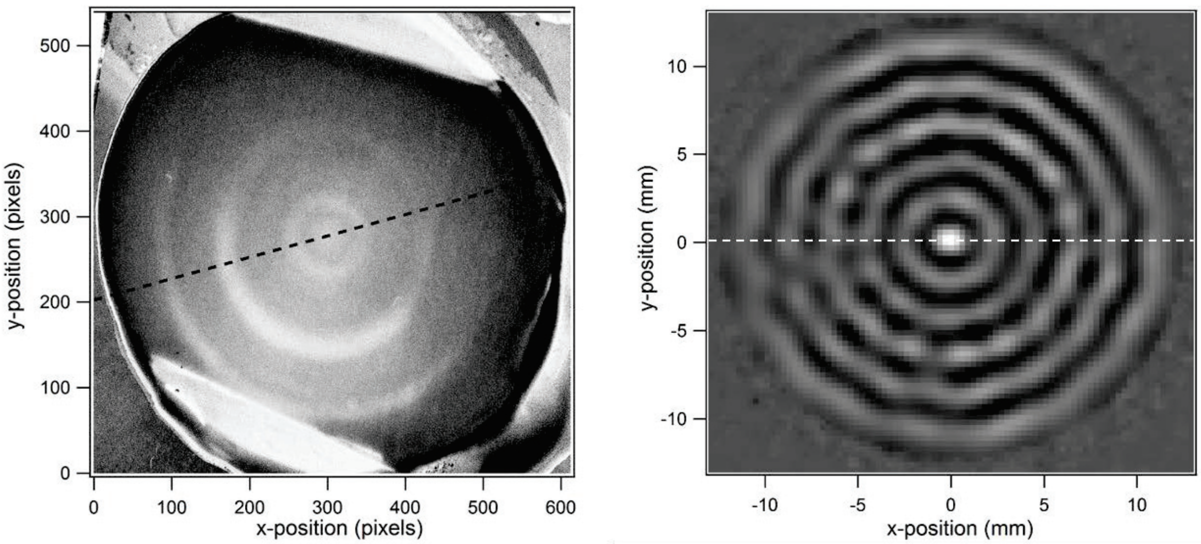


**FIGURE 4.** Imaging of the (0,11) mode of the flexural transducer. The left image is a photograph of acoustic clearing in the PDLC layer, while the right image is the wavefield measured using a vibrometer. The line across each corresponds to the measurement shown in figure 5. Colour images are available in reference [11].

To quantify the changes, the photograph of the clearing of the PDLC layer was analysed by taking a straight line across the transducer (shown as the dashed line in figure 4) with the amplitude of the greyscale image taken at each point along the line. The results of this analysis are shown in figure 5 as a solid line, with the scan position approximated from the photograph using knowledge of the size of the transducer. Similarly, amplitudes were recorded across the dashed line shown for the vibrometer measurements in figure 4, and are plotted in figure 5 as a dashed line. The main peaks align well, with similar peak features shown in both graphs. Whilst the vibrometer image produces cleaner data, it should be noted that the PDLC layer was an initial prototype and the methods and analysis will be significantly improved through further research. This shows significant promise for its use in transducer characterisation, with the data taken in a tiny fraction of the time required for a vibrometer scan.

The presence of peaks and dips in the acoustic clearing confirms that the acousto-optic effect has been observed. In addition, the PDLC was measured during operation using a thermal imaging camera with a 25 mK sensitivity. The clearing occurred while the transducer was below the temperature required for full clearing of the PDLC; when the amplitude of vibrations was increased such that the PDLC layer completely cleared, the relaxation back to opaque once the transducer was switched off took around 30 s. This is in contract to the acoustic clearing, which took 1-2 s to return to the opaque state. Some pre-heating is beneficial – it enables a quicker transition when turning on the transducer, as LCs become more sensitive near the thermally-induced transition to isotropic state.

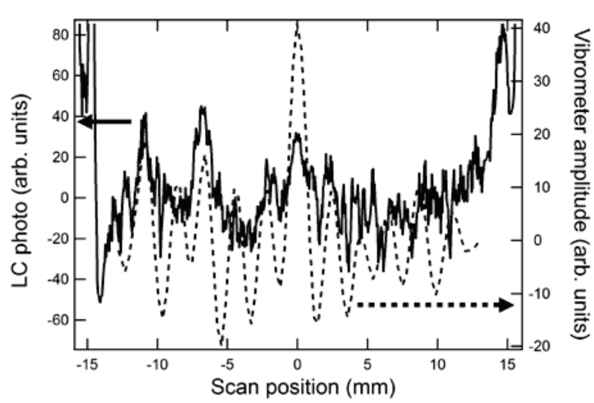


**FIGURE 5.** Amplitude taken from the greyscale image of acoustic clearing (solid line) and from vibrometer measurements (dashed line).

## CONCLUSIONS

PDLC acoustic sensors offer many potential advantages for NDE. They can be produced at relatively low cost, due to the ability to produce sensors made from thin layers of PDLC. This in turn makes it feasible to produce large area sensors. The operation is significantly simplified compared to working with LCs due to removing the requirement for pre-alignment, and limited scanning is required for characterization of transducers. They offer a very high potential resolution, limited by the droplet size, and appear to be sensitive to both longitudinal and surface acoustic waves. The measurement is passive, not requiring any electronics other than a camera for recording of the patterns produced. Fast relaxation of 1-2 s is possible.

The use of PDLCs as ultrasound sensors, however, requires more work. It is important to understand the physics behind the acousto-optic effect in PDLC, as there are contrasting opinions on its mechanisms [2-4]. The sensitivity to smaller wave amplitudes needs to be enhanced. Further investigation of different LC and polymer materials is required to find the optimal combination for NDE.

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